

Introduction of High Differential Pressure Water Electrolysis-type Solar Hydrogen Station (SHS2)

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ABSTRACT

A high differential pressure water electrolysis-type solar hydrogen station (SHS2) was built with installation in ordinary households in mind. This SHS2 was equipped with a newly developed high differential pressure electrolyzer, which is an innovative technology. The stack differs from the ordinary high-pressure electrolyzer that keeps both the anode side and the cathode side in a high-pressure state. Here, instead, the anode side is under normal pressure and only the cathode side is maintained under the high pressure of 35 MPa. Compared to the ordinary high-pressure electrolyzer, therefore, this one has a simpler structure and can be made compact. Furthermore, the stack here has the functions of both generating and compressing hydrogen, so that the SHS2 with this stack mounted was made into a compact, highly efficient and low-noise, home-sized hydrogen refueling appliance.

Compared to the previous solar hydrogen station (SHS1), the SHS2 is 60% more compact and realizes an increase of 25% in system efficiency.

1. Introduction

Honda has engaged in the development of fuel cell electric vehicles based on its understanding that fuel cells utilizing hydrogen are the ultimate next-generation powerplant in terms of providing an alternative to fossil fuels, reducing emissions, and minimizing the impact on global warming.

It is desirable to use sustainable energy sources in the process of manufacturing the hydrogen that is the fuel for fuel cell electric vehicles, in order to minimize the use of fossil fuels and reduce CO₂ emissions. For reasons like these, we are also conducting research and development of a solar hydrogen station that uses solar cells for the source of input power. This should contribute to the formation of a hydrogen society in the future. Testing began in July 2001 at the Los Angeles Center campus of Honda R&D Americas in Torrance, California, USA, using a combination of commercially available equipment. The SHS1 entered operation in October 2003, with a water electrolyzer, which was our proprietary technology, and a prototype CIGS (copper, indium, gallium, and selenium compounds) thin film solar cell^{(1),(2)}.

The results⁽³⁾ from proving tests of the SHS1 conducted to date suggest that a renewable hydrogen station of a

size suitable for household use would require still greater compactness and higher efficiency. It became clear, as a point of approach for this, that it would be important to reduce the dehumidification energy and the compression energy of hydrogen.

The SHS2 is an evolved form of the SHS1 for ordinary household use. It involved updating the SHS1 and installing it at the Los Angeles Center campus of Honda R&D Americas, where it entered operation in January 2010. This article will introduce the SHS2 design, the performance of the station, and the technology of the high differential pressure electrolyzer.

2. Concept and Design of the High Differential Pressure Water Electrolysis-type Hydrogen Station (SHS2)

2.1. Concept

Figure 1 shows an exterior view of the SHS2 that is discussed here.

The concept for the SHS2 was defined as “Intuitive and Integrated.” Therefore, the dispenser unit, which requires the user to perform hydrogen filling operations, was designed to allow superior operability with an intuitive quality. With the electrolysis unit, the aim was to achieve

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Fig. 1 External view of high differential pressure water electrolysis-type Solar Hydrogen Station (SHS2)

greater compactness by integrating the hydrogen generating and compressing functions.

2.2. Steps Toward Installation in Households

In order to install the SHS2 in households, it is necessary to make it seem approachable and non-intimidating to users. Since it should not give the user an overpowering impression, the shape of the station as a whole, as well as of the component units, was designed deliberately not to have any sharp angular lines. By giving them rounded curves, they were made to convey a sense of security and accessibility. The component units were also made compact so as to fit the human sensibility and to be of a size not to intimidate users or give them an impression of being overpowered.

If the SHS2 is envisioned as installed in the garage of a domestic dwelling, then the dispenser unit that is accessed by users will be located inside the garage. Here, therefore, the SHS2 was configured with a scoop-shaped structure, intended to seem as though wall-mounted in the garage, with a dispenser unit placed in front of it and the electrolysis unit located behind it.

Previously, there had been seven round concrete columns 150 mm in diameter and 900 mm in height, called bollards, placed in front of the units at approximately 1600 mm intervals to protect them from being hit by a car. Instead of using bollards this time, however, curving sidewalls were built on either side of the units and the unit bases were raised approximately 150 mm (6 inches) above the roadway level as measures to protect against collision. This enabled the external appearance of the SHS2 to be

given a simple, non-intimidating appearance that would not give the user an impression of being overpowered.

2.3. Packaging

Figure 2 shows the external appearance of the electrolysis unit. The electrolysis unit was built on the assumption of outdoor installation, so environmental factors such as rain and wind have been taken into consideration. In terms of shape, it was made simple with curved surfaces, for a styling that does not make it seem intimidating.



Fig. 2 Electrolysis unit

Figure 3 shows the external appearance of the dispenser unit and scoop. The height of the units was determined by the placement of the user interface (UI), and their width by the allowable bending radius of the fueling hose. Operability and usability were taken into consideration by fabricating actual-size mockups and checking the method of housing the fueling nozzle and the length of the hose in advance.

2.4. User Interface (UI)

Figure 4 shows the UI screen display. The screen

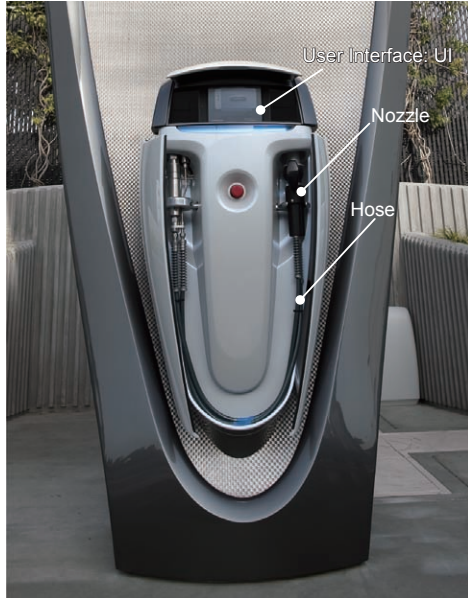


Fig. 3 Dispenser unit with User Interface

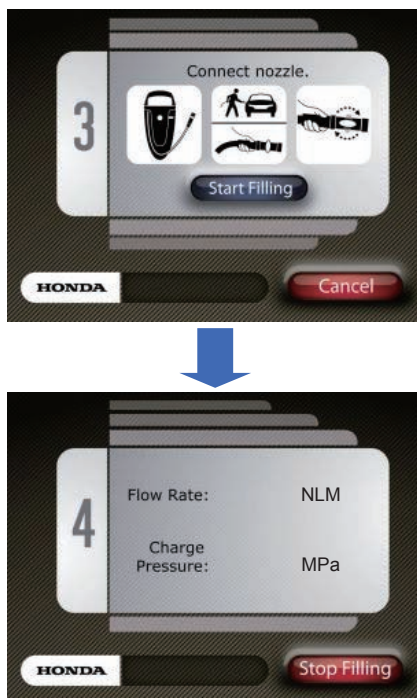


Fig. 4 UI screen

display has been simplified and conveys an adequate amount of necessary information in order to make it acceptable to ordinary users. The display is organized by layered menus, and the operational diagrams are designed to be intuitive and easy to understand.

The user connects the hydrogen fueling nozzle in the dispenser unit to the fuel cell electric vehicle, then presses the start button (Start Filling) on the display. This causes hydrogen filling to begin. Then the user can press the stop button (Stop Filling), or hydrogen filling ends automatically when the tank on the fuel cell electric vehicle reaches the full state (35 MPa).

3. System Overview of the High Differential Pressure Water Electrolysis-type Hydrogen Station (SHS2)

3.1. System Configuration

Figure 5 shows a comparison of the system configuration in the SHS1 and SHS2 hydrogen stations.

In the SHS1, hydrogen was generated at normal pressure (max. 0.12 MPa) in the water electrolyzer, and hydrogen compression was carried out in the mechanical compressor. The SHS2, on the other hand, is equipped with a high differential pressure electrolyzer that integrates the hydrogen compression function into the water electrolyzer. The high differential pressure electrolyzer is unlike the mechanical compressor in that there are no sounds of vibration or motor operation when hydrogen compression is taking place, so it is very quiet. Furthermore, it uses an electrochemical method of hydrogen compression, so it is highly efficient and not subject to the kind of friction loss or motor loss found in a mechanical compressor. Furthermore, the elimination of the mechanical compressor and update of the system configuration enabled greater compactness, with an approximately 60% reduction in volume of the electrolysis unit compared to the SHS1. Consequently, the SHS2 equipped with a high differential pressure electrolyzer is an effective choice for installation in ordinary households.

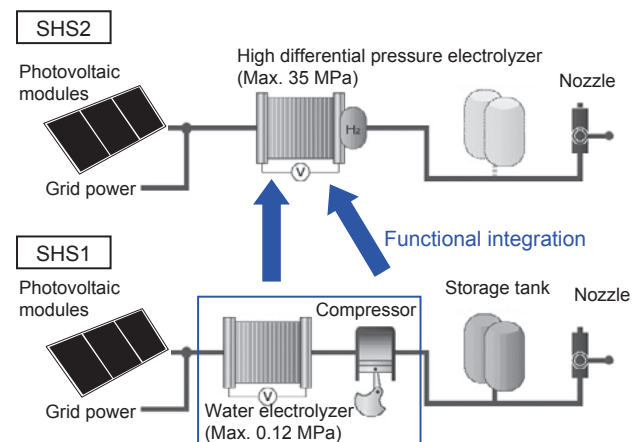


Fig. 5 Comparison of solar hydrogen stations

Table 1 Specifications of SHS2

Hydrogen production	Flow rate	0.7 Nm ³ /h (0.5kg/8h)
	Filling pressure	35 MPa (max.) (approx. 5000 psi)
	Purity	> 99.99%
Component	Photovoltaic modules	CIGS thin film solar cell 6 kW system (approx. 53 m ²)
	Electrolysis unit	High differential pressure electrolyzer
Utility	Electricity	240 VAC
	Water	Tap water
Unit volume		Approx. 0.33 m ³ (approx. 12 cf)

3.2. Specifications

Table 1 shows the SHS2 specifications.

The SHS2 is like the SHS1 in being equipped with a 6-kW capacity CIGS thin film solar cell manufactured by Honda Soltec Co., Ltd. The system was designed to use 240 VAC, which is already available in most average households in the USA, as its input power. The electric power generated by the solar cells during daylight is exported over the grid, and the electric power to operate the system at night is imported from the grid. The system only needs to be supplied with tap water and electricity to operate, and it is able to fill the fuel cell electric vehicle with high-purity hydrogen under maximum pressure of 35 MPa. The hydrogen production volume is approximately 0.7 Nm³ per hour. If a Honda FCX Clarity is filled up with hydrogen generated over an eight-hour period at night, when electricity rates are lower, it will be able to drive approximately 30 miles⁽⁴⁾ (50 km) the next day. The present system does not have a fixed emplacement of high-pressure storage tanks, but installation of such tanks would enable fast filling of a fuel cell electric vehicle. Furthermore, the system is capable of manufacturing hydrogen with electric power from its solar cells during the day, so it could be operated for 24 hours and store the hydrogen in the tanks, in which case it could manufacture enough hydrogen to drive the car approximately 90 miles (150 km) in a day.

One purpose of proving tests is to evaluate the durability and reliability of component parts over a long period of time. For that reason, the hydrogen pressure inside the high differential pressure water electrolyzer system is not linked with the tank pressure in the fuel cell electric vehicle. Instead, it is designed to maintain a pressure of 35 MPa, and evaluation of its durability and reliability can therefore be conducted under very demanding pressure conditions.

4. Initial Performance Evaluation of the High Differential Pressure Water Electrolysis-type Hydrogen Station (SHS2)

4.1. Fueling Test of Fuel Cell Electric Vehicle

Figure 6 shows the results of hydrogen filling tests carried out with the fueling nozzle connected to a fuel cell electric vehicle.

Figure 6(a) shows changes in the data over a 20-minute system start-up period after the start button on the UI screen has been pressed. As preparation for start-up, the interiors of the electrolysis unit and dispenser unit are first ventilated, and the equipment, piping, and so on are checked to make certain there are no hydrogen leaks. Then an initial check of sensors is carried out to determine whether the system is in a state capable of coming on line. If the check results are normal, then the pure water generator is started up, the water circulation pump is started up, completing the preparations for operation. The time taken to complete preparations for operation is largely determined by the pure water generator start-up time. Figure 6(a) shows the preparations for operation were complete after approximately 6 minutes. Once the preparations for operation have been completed, then voltage is supplied to the high differential pressure electrolyzer and electrolysis of water begins. The hydrogen pressure in the high differential pressure electrolyzer starts at normal pressure, and when it reaches 35 MPa, the hydrogen starts flowing outside the system, the fuel cell electric vehicle starts filling, and the vehicle tank pressure gradually starts rising. In the present tests, hydrogen filling

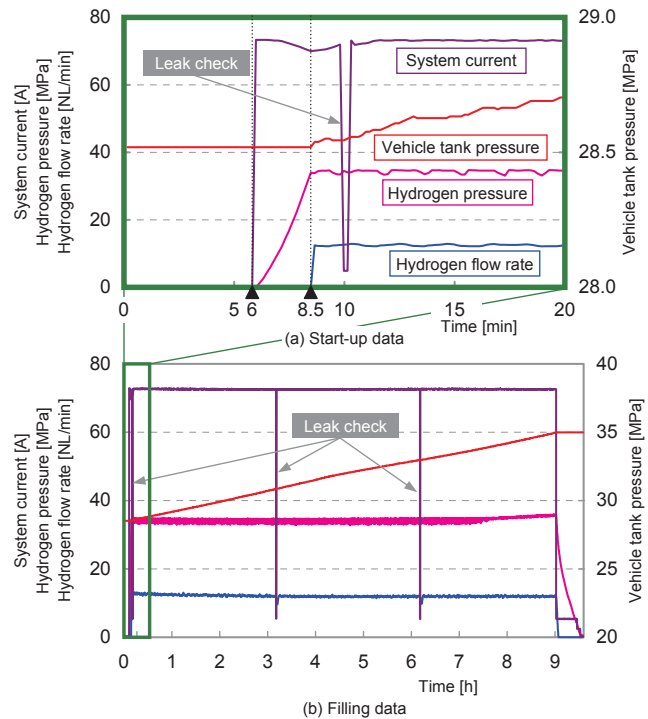


Fig. 6 System operating result for one day in January 2010

of the fuel cell electric vehicle started approximately 8.5 minutes after the start button was pressed, indicating that the differential pressure electrolyzer had finished starting up after only 2.5 minutes.

Consideration has also been given to the safety of ordinary users. In order to check that the fueling nozzle is securely connected to the fuel cell electric vehicle, hydrogen production is temporarily stopped immediately after hydrogen filling of the fuel cell electric vehicle begins, and a leak check is conducted for approximately 20 seconds to determine whether there is any drop in pressure due to a hydrogen leak in the nozzle connector.

Figure 6(b) shows the results of the series of filling tests conducted this time. In addition to the initial leak check shown in Fig. 6(a), checks are also conducted every three hours during hydrogen filling to make certain there are no leaks from the nozzle connector and hose. When the hydrogen filling is to be stopped, either the user presses the stop button on the UI screen or the tank pressure in the fuel cell electric vehicle reaches the full state of 35 MPa, at which time the system automatically stops operating. These tests confirmed that the system stopped when the tank became full approximately nine hours after the start button was pressed, when the tank pressure in the fuel cell electric vehicle had risen from about 28.5 MPa to about 35 MPa.

4.2. Hydrogen Quality

The quality of the hydrogen supplied to fuel cell electric vehicles is prescribed in ISO 14687 (Hydrogen fuel – Product specification)⁽⁵⁾. The quality of hydrogen obtained through operation of the SHS2 is shown in Table 2.

The SHS2 electrolyzes purified water to obtain hydrogen. As a result, the only contaminants contained in the hydrogen are oxygen and moisture. It is characteristic of the high differential pressure electrolysis cell that the cathode side is maintained at high pressure, with a solid polymer membrane (proton exchange membrane: PEM) separating it, while the anode side, where oxygen is generated, is at atmospheric pressure. Consequently, the amount of oxygen that diffuses to the high-pressure cathode side is very small, reaching a level of 5 ppm or less, even though no process is carried out to lower the concentration of oxygen in the hydrogen. As for moisture, it is removed by an adsorbent placed in a later stage of the high differential pressure electrolyzer.

The hydrogen quality measurement results show that the hydrogen produced by the SHS2 clears the ISO 14687-2 standards and is of a quality adequate for use in fuel cell electric vehicles.

4.3. System Efficiency

Figure 7 shows the energy expended in compression and dehumidification at a hydrogen pressure of 35 MPa in the SHS2 and SHS1.

The energy consumption of the low flow rate mechanical compressor intended for use in small stations

Table 2 Hydrogen quality of SHS2

	ISO14687-2	SHS2
H ₂	>99.99%	>99.99%
H ₂ O	<5 ppm	<1 ppm
Hydrocarbon	<2 ppm	<0.1 ppm
O ₂	<5 ppm	1 ppm
He, Ar, N ₂	<100 ppm	<16 ppm
CO ₂	<1 ppm	<0.1 ppm
CO	<0.2 ppm	<0.001 ppm
Sulfur	<0.004 ppm	<0.0008 ppm
HCHO	<0.01 ppm	<0.001 ppm
HCOOH	<0.2 ppm	<0.001 ppm
NH ₃	<0.1 ppm	<0.02 ppm
Halogenates	<0.05 ppm	<0.004 ppm

and installed in the SHS1 shows a greater influence from friction loss than a high flow rate compressor, and the hydrogen compression energy is greater. Meanwhile, the high differential pressure electrolyzer installed in the SHS2 uses electrochemical compression by means of a PEM, so there is no friction loss or motor loss. As a result, the hydrogen compression energy is lower, making this a more efficient method of hydrogen compression. According to ISO 14687-2, the allowable amount of moisture in the hydrogen for use in fuel cell electric vehicles is under 5 ppm. It is therefore necessary to conduct dehumidification of the hydrogen produced.

The hydrogen produced by the water electrolyzer in the SHS1 reached a pressure of approximately 0.1 MPa, so the water content of the hydrogen was high, at approximately 35800 ppm. At a later stage in the water electrolyzer, a Peltier cooling-type condenser was installed in order to reduce this water content by cooling the hydrogen and lowering the amount of saturated vapor. Most of the cooling energy was used in condensation of the water vapor. A thermal swing adsorption (TSA)-type adsorber was also

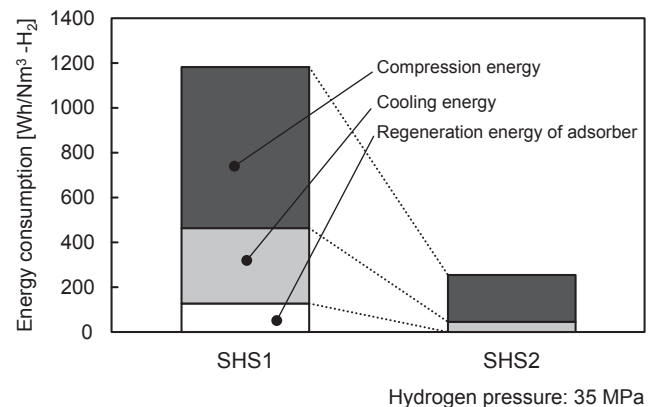


Fig. 7 Comparison of power consumption

placed at an earlier stage of the compressor, and this imposed a regeneration energy requirement on the adsorber for the electric heater.

Meanwhile, the hydrogen produced by the high differential pressure electrolyzer in the SHS2 was at a higher pressure of 35 MPa, so that the water content of the hydrogen was approximately 100 ppm. This was approximately one 350th or less of the amount in the SHS1. This means that the energy for Peltier cooling (cooling energy) is notably lower. The adsorber placed in a later stage of the Peltier cooling-type condenser also had an internal capacity of approximately 700 cm³, and the adsorbent placed there would thereby maintain its adsorbent performance for half a year or more. This time, therefore, a replacement adsorber was adopted in place of a regenerative adsorber, making a system that had no need for regeneration energy. As a result of these differences, the energy required for compression and dehumidification came to approximately one-fourth that in the SHS1.

Mounting a high differential pressure electrolyzer not only enabled a reduction in the energy required for compression and dehumidification, it also allowed the system to be simplified so that the power for solenoid valves and other auxiliary devices could be reduced. As a result, the SHS2 has achieved a 25% boost in system efficiency relative to the SHS1.

5. High Differential Pressure Electrolyzer

5.1. Principle of High Differential Pressure Electrolysis

Figure 8 shows the schematic of a high differential pressure electrolysis cell.

In electrolysis cells that use PEMs when purified water is supplied and a voltage is continuously applied to the PEM, the cells will continue to generate oxygen and hydrogen. Therefore, if a high-pressure tank is placed at

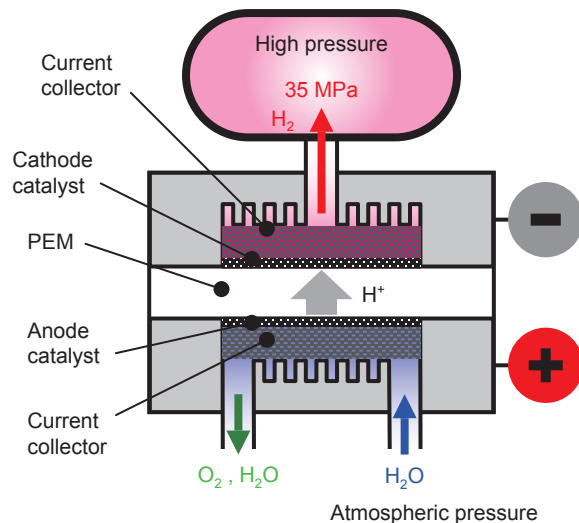
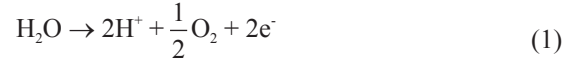


Fig. 8 Schematic of high differential pressure electrolysis cell

the hydrogen exit side, the pressure inside the tank will gradually continue rising and high pressure hydrogen will eventually be obtained. The oxygen, on the other hand, is at atmospheric pressure, which is why a pressure difference is created in a high differential pressure electrolysis cell with a PEM separating the different pressure areas.

Equations (1) and (2) show the reactions that occur in high differential pressure electrolysis.



When a voltage is applied across the PEM, the purified water on the anode side becomes oxygen and protons H⁺. The protons travel to the counter electrode and form hydrogen. This phenomenon is the same as in ordinary water electrolysis, but when the protons travel to the counter electrode, an electromotive force should be applied because of the partial pressure difference in the hydrogen.

Equation (3) shows the electrolysis voltage E_{WE} required in high differential pressure electrolysis.

$$E_{WE} = E_1 + \frac{RT}{2F} \ln \frac{P_1}{P_2} + ir \quad (3)$$

R : Gas constant

T : Absolute temperature

F : Faraday constant

P_1 : Hydrogen partial pressure of high pressure side

P_2 : Hydrogen partial pressure of low pressure side

In addition to the theoretical electrolysis voltage E_1 of water electrolysis and the cell resistance ir , high differential pressure electrolysis occurs through application of the potential difference in hydrogen concentration required in a gas concentration cell⁽⁶⁾. The second term on the right side of Eq. (3) will be the Nernst electromotive force needed from the Nernst equation hydrogen concentration difference.

5.2. Results of High Differential Pressure Electrolyzer Performance Evaluation

Figure 9 shows two sets of values for the energy consumption when the high differential pressure electrolyzer is used to electrolyze water and the generated hydrogen is compressed from normal pressure to 35 MPa. One is the actual measured value for energy consumption and the other is the calculated value derived from Eq. (3).

With the hydrogen at normal pressure, the total energy consumption was approximately 4000 Wh/Nm³, of which 3544 Wh/Nm³ was the theoretical electrolysis energy (hydrogen conversion energy), and the remainder was the cell resistance. The cell resistance includes contact resistances and membrane resistance between the

membrane and the electrode and between the electrode and the collector, as well as anodic and cathodic overvoltages and ohmic dissipation.

With the hydrogen pressure at 35 MPa, the compression energy is approximately 200 Wh/Nm³. Compared to

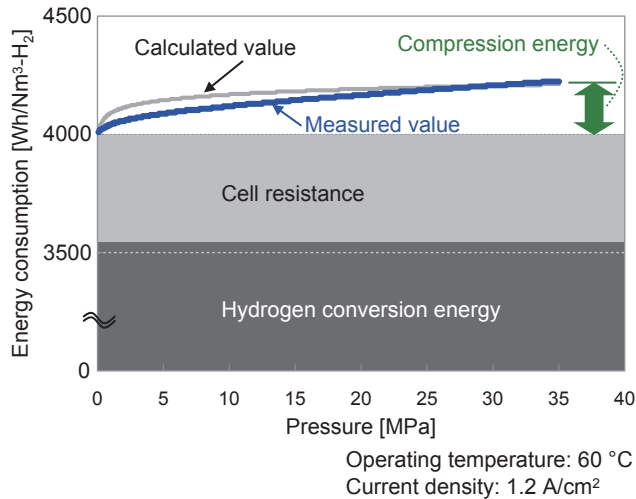


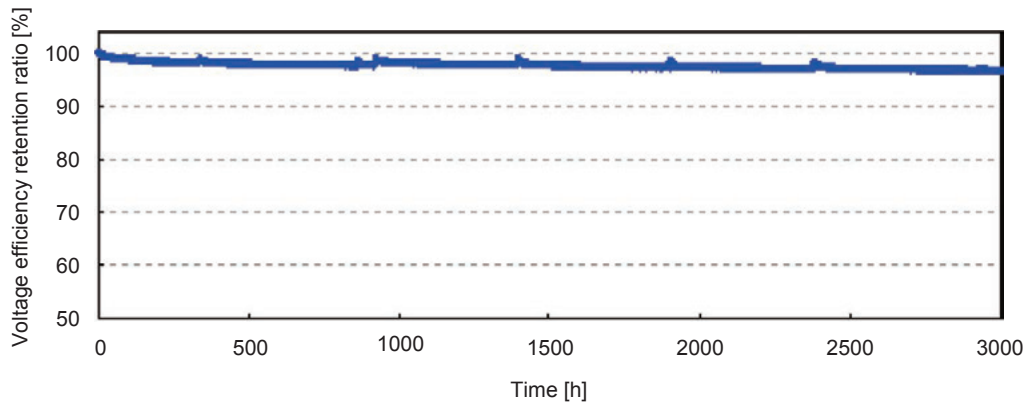
Fig. 9 Hydrogen compression curve of high differential pressure electrolyzer

the compression energy of 700 Wh/Nm³ for the SHS1 mechanical compressor shown in Fig. 7, the compression energy required for the high differential pressure electrolyzer is small, and it also coincided with the calculated value. In the low-pressure range, however, the actual measured values for energy consumption were lower than the calculated value, and this is thought to be because of a decrease in cell resistance components – primarily a decrease in contact resistances between the membrane and the electrode and a decrease in membrane resistance due to changes in membrane thickness – that occurred as the pressure increased.

The total energy consumption by the high differential pressure electrolyzer with the hydrogen pressure at 35 MPa was 4200 Wh/Nm³, showing an efficiency of approximately 84% relative to the theoretical electrolysis energy (3544 Wh/Nm³). The SHS2 can be considered an energy conserver as a high-pressure hydrogen generator.

5.3. Durability of the High Differential Pressure Electrolyzer

A unit durability test of the high differential pressure electrolyzer was carried out at a hydrogen pressure of 35 MPa. Since the SHS2 was envisioned as operating for



(a) Trend of voltage efficiency retention ratio

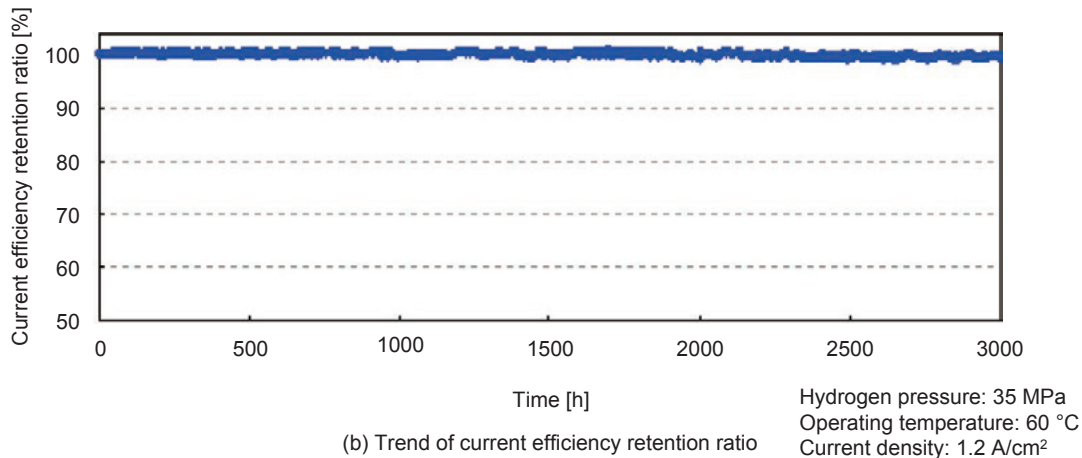


Fig. 10 Durability performance of high differential pressure electrolyzer

eight hours per day, 3000 hours amounts to approximately one year of operation. Figure 10 shows (a) the voltage efficiency retention rate and (b) the current efficiency retention rate of the high differential pressure electrolyzer.

The high differential pressure electrolyzer shows no sharp declines in voltage efficiency. After 3000 hours, there was a change of approximately 4%. This decrease in performance coincided closely with the decrease in performance of the water electrolyzer. It appears likely, therefore, that no increase over time took place in membrane resistance due to high-pressure hydrogen, nor any degradation in catalytic performance, nor any increase in contact resistances due to deformation of current collectors or other such stack components.

The current efficiency retention rate remained constant from the beginning through 3000 hours. The performance in high-pressure hydrogen production remained stable. No hydrogen leak to the outside of the stack was observed throughout the durability test.

Given the above, and given that the high differential pressure electrolysis displayed no particular change in durability, but retained its efficiency at a rate equivalent to a water electrolyzer, the prospective outcome of long-term durability proving tests of the SHS2 using this stack became apparent.

6. Conclusions

The installation of the high differential pressure water electrolysis-type solar hydrogen station (SHS2), which has the purpose of reducing CO₂ emissions, and initial performance evaluations of the SHS2 yielded the following results:

- (1) The SHS2 was developed with installation in ordinary households in mind, and consideration was given accordingly to its safety and operability. Compared with the SHS1, the SHS2 was made approximately 60% more compact, realizing a size that allows installation in average households.
- (2) The development of a highly efficient, high differential pressure electrolyzer system meant that the SHS2 achieved a system efficiency 25% higher than that of the SHS1.
- (3) The efficiency of hydrogen production at 35 MPa using a high differential pressure electrolyzer is approximately 84%. This showed that the SHS2 is a high-pressure hydrogen generator that operates with greater energy-saving than the SHS1, which used a water electrolyzer with a mechanical compressor.
- (4) The high differential pressure electrolyzer unit was subjected to durability testing equivalent to one year of operation. The results showed that the change in power efficiency it underwent was the same as the change in efficiency undergone by a water electrolyzer.

The high differential pressure water electrolysis-type solar hydrogen station (SHS2) will be subjected to proving

tests, and the feasibility of its function and performance in actual environmental conditions will be confirmed.

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